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(54) Title: METHOD AND APPARATUS FOR PULSED PLASMA-MEDIATED ELECTROSURGERY IN LIQUID MEDIA

(57) Abstract

This invention is a method for performing electrosurgery using sub-mircosecond, high-power electrical pulses applied to an electrosurgical probe endface (60). The probe endface has an area of about 200 microns to 1000 microns^2. The pulses have a duration less than 300 nanoseconds, and preferably have very fast rise times, and very fast fall times (e.g., less than 1000 nanoseconds). The pulses also have power dissipation greater than 500 Watts (e.g. 800 Watts ato 2500 Watts), or voltage greater than 1.5 kV (e.g. 2kV to 3 kV). These pulse characteristics provide for reduced collateral damage, and effective cutting of tissues. Cutting is mainly provided by plasma streamers (65) which are formed on the probe tip end face. However, cutting is also provided by shock waves formed by the discharges. The method is applicable to microsurgical procedures such as retinal surgery and capsulotomy. Also disclosed are electrical circuits (21, 90) for performing the method.

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Method and Apparatus for Pulsed Plasma-Mediated Electrosurgery in Liquid Media

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FIELD OF THE INVENTION

15 This invention relates generally to electrosurgery. More particularly, it relates to a method for electrosurgery using short duration, high voltage pulses in liquid.

BACKGROUND OF THE INVENTION

20 Electrosurgery is a technique used in the medical arts for cutting, ablation and coagulation of tissues. In electrosurgery, electrical energy is applied to the tissue or to conductive media in proximity to the tissue. The electrical energy can heat, evaporate and ionize the tissue.

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Most commonly in electrosurgery, the electrical energy is applied as a continuous wave (CW) or pulses of radiofrequency energy. The RF energy is applied with a probe having a pair (or more) of electrodes. Tissues in proximity to the electrodes is 30 heated and destroyed or ablated. Electrosurgery with RF energy is usually used in medical procedures where direct heating is desired for tissue modification, destruction, or removal. Examples of such procedures include coagulation of blood vessels, tissue dissection in general surgery (electric knife), 35 and skin and cartilage removal.

A shortcoming of using RF energy in electrosurgery is that, for some applications, the RF energy heats too broad a region, resulting in undesired collateral damage to surrounding tissues. 40 Use of RF energy is particularly undesirable for delicate microsurgical procedures where RF energy tends to result in unacceptably large areas of collateral damage.

5   Certain pulsed electrosurgical devices have been proposed for
     specific applications. R. Vorreuther et al. Journal of Urology,
     153:849-853 (1995) use high energy pulses (tens of milliJoules)
     with a relatively long duration (hundreds of microseconds) to
     generate shock waves which destroy the targeted tissue (e.g.
10   kidney stones). The method of Vorreuther obviously cannot be
     applied to delicate microsurgical procedures. Also, the long
     pulse durations taught by Vorreuther tend to result in excessive
     collateral damage. Another disadvantage of the teachings of
     Vorreuther is that the device has a short lifetime of less than
15   100 pulses due to the high energy of the pulses.

     US Patent 4,429,694 discloses an electrosurgical technique where
     AC voltage pulses are used to coagulate tissues by heat
     generation. The AC pulses generate plasma in air which is
20   applied to the tissues to be coagulated. US Patent 5,300,068
     teaches the use of relatively long duration pulses (about 200
     microseconds) for electrosurgery. US Patent 5,509,916 discloses
     the combination of laser pulses and electrical pulses. The
     laser pulse provides more precise localization of the electrical
25   discharges. The prior art does not teach methods for precise
     electrosurgical cutting of tissues applicable to microsurgery in
     liquid where a very small (tens of microns or less) collateral
     damage zone is important.

30   "Electrical Alternative to Pulsed Lasers in Microsurgery",
     Journal of Applied Physics 81(11): 7673-76780 (1997) by Daniel
     Palanker et al. discloses a method for intraocular microsurgery
     based on cavitation bubble generation by electrical discharge.
     In this approach, the expanding cavitation bubble is used to
35   provide cutting action. A limitation of using the cavitation
     bubble for cutting is that only very soft tissues (e.g. retinal
     tissues) can be cut. Relatively hard tissues such as eye
     lenses, lens capsules (e.g. in a capsulotomy procedure) or
     irises cannot be cut by the method disclosed by Palanker. Yet
40   another disadvantage of the method of Palanker is that
     cavitation bubbles produce substantial collateral damage to
     surrounding tissues due to generation of water flow during
     bubble collapse.

5   Pulsed lasers have commonly been used in delicate surgical
         procedures where collateral damage must be avoided (i.e.
         vitreoretinal surgery). However, a great disadvantage of laser-
         based devices is that they are relatively expensive, costing
10   upwards of $100,000. Electrosurgical systems are typically much
         less expensive.

OBJECTS AND ADVANTAGES OF THE INVENTION
         Accordingly, it is a primary object of the present invention to
15   provide an improved method for electrosurgery that:

         1) produces very little collateral damage to tissues surrounding
         targeted tissues;

20   2) is capable of cutting relatively hard tissues such as lenses,
         lens capsules, and irises;

         3) is less expensive than laser based surgical devices;

25   4) can be used in microsurgical procedures;

         5) is capable of precise dissection of biological tissue in
         liquid media.

30   These and other objects and advantages will be apparent upon
         reading the following description and accompanying drawings.

SUMMARY OF THE INVENTION
         These objects and advantages are attained by a method for using
35   an electrosurgical probe immersed in liquid media or tissue.
         The electrosurgical probe has a first electrode and a second
         electrode. The first electrode has an endface area A in close
         proximity to tissue to be cut. The method has the step of
         applying to the first electrode an electrical pulse such that
40   plasma streamers are formed from the endface. The plasma
         streamers develop in the liquid medium or tissue. The
         electrical pulse has a voltage of at least 1.5kV for a nonzero
         duration of less than 300 nanoseconds. The electrical pulse has

5   a 100 volt to 1.5kV V-risetime of less than 100 nanoseconds, and
     a 1.5kV to 100 volt V-falltime of less than 300 nanoseconds.
     The endface area is less than 10000 microns^2.

     The present invention also includes the method of applying to
10   the first electrode an electrical pulse wherein the pulse
     dissipates at least 500 Watts for a nonzero duration less than
     300 nanoseconds. The pulse has a P-risetime from 50 Watts to
     500 Watts of less than 100 nanoseconds. Also, the pulse has a
     P-falltime from 500 Watts to 50 Watts of less than 150
15   nanoseconds. The endface area A is less than 10000 microns^2.

     The present method can also be characterized in terms of a peak
     power dissipation of the pulse. In this characterization, the
     pulse has a power dissipation greater than 500 watts for a
20   duration less than 300 nanoseconds. The pulse has a risetime
     from 10% of peak power to 90% of peak power which is less than
     100 nanoseconds. The pulse also has a falltime from 90% of peak
     power to 10% of peak power less than 200 nanoseconds. The peak
     power dissipation can be greater than 800 Watts, 1000 Watts, or
25   1500 Watts, for example.

     The present invention also includes an apparatus for
     electrosurgically cutting tissue according to the present
     invention. The apparatus has a high voltage source for
30   providing a voltage of at least 2kV, a probe, a discharge
     switch, and a shunt switch. The probe has a first electrode and
     a second electrode. The discharge switch is connected between
     the high voltage source and first electrode such that, when
     closed, the discharge switch applies high voltage to the first
35   electrode. The shunt switch is connected between the first and
     second electrodes.

     Alternatively, the shunt switch is replaced with only a shunt
     resistor. In this case, the shunt resistor has a resistance
40   lower than a normal state (i.e. no plasma present) resistance
     between the first and second electrodes. Preferably, the shunt
     resistor has a resistance in the range of 1-5kOhm.

DESCRIPTION OF THE FIGURES

Fig. 1 shows a preferred embodiment of the present invention in use cutting tissue.

Fig. 2 shows a closeup view of a probe tip of the present invention.

Fig. 3 shows a characterization of electrical pulses according to the method of the present invention.

Fig. 4 shows the probe tip while an electrical pulse is applied to the probe.

Figs. 5A-5B show different modes of using the present invention.

Fig. 6A shows a characterization of electrical pulses of the present invention in terms of power.

Fig. 6B shows a second characterization of electrical pulses of the present invention in terms of power.

Fig. 7 shows a second embodiment of the present invention for producing electrical pulses.

Fig. 8 shows a power versus time plot of a pulse train according to the present invention.

DETAILED DESCRIPTION

The present invention provides methods for cutting tissues in liquid media using short duration electrical discharges. The electrical discharges used have sufficient power dissipated from a sufficiently small electrode surface so that plasma streamers are produced which extend from the electrode surface. The plasma streamers are produced in the tissue or liquid medium surrounding the tissue. The plasma streamers ionize and evaporate tissue (or liquid), thereby producing high pressure shock and acoustic waves. The high temperature of the plasma streamers and the shock waves produced provide effective cutting of tissue. The electrode surface is preferably in contact with the tissue being cut, but can also be spaced apart from the tissue being cut. The present invention uses DC electrical pulses.

Fig. 1 shows a preferred electrical circuit **21** for performing the method of the present invention. The apparatus has a high voltage supply **20**. The supply **20** provides 2-10 kilovolts, for

5   example.   The voltage supply **20** is connected to a capacitor **22**
     (e.g. at least 10-50 picofarads) and a high speed, high voltage
     discharge switch **24**.   The discharge switch is connected to a
     discharge resistor (R1) **26**, a shunt switch **28**, a shunt resistor
     (R2) **30**, and an electrosurgical probe **32**.   The discharge switch
10   **24** and shunt switch **28** are controlled by switch controller **34**.
     The electrosurgical probe **32** is shown in contact with tissue **36**
     to be electrosurgically cut.   The tissue **36** to be cut is
     surrounded by conductive liquid media **35** such as tissue fluid,
     intraocular fluid, or other physiological liquids.   The liquid
15   **35** may be present in a thin layer (e.g. less than 0.1 mm thick)
     covering the tissue **36**.

     Probe **34** has two electrodes: an inner electrode **38** and a coaxial
     outer electrode **40**.   The inner electrode and outer electrode are
20   separated by a dielectric material **42** such as glass or fused
     silica.   The outer electrode **40** has a much larger surface area
     compared to inner electrode **38**.   The liquid media **35** is in
     contact with the outer electrode **40**.   Outer electrode is always
     connected to ground.   The probe has a tip **37** where the inner
25   electrode **38** is not covered by dielectric material **42**.   The
     probe has a diameter **41** of about 1.0 mm, tapering to 0.2 mm near
     the tip **37**.   Alternatively, the probe **34** may have a non-coaxial
     geometry such as two electrodes with comparable exposed surface
     areas embedded in insulating material.   Many electrosurgical
30   probes are known in the art.

     In performing the method of the present invention, the outer
     electrode **40** can also be in contact with the tissue **36**.   This
     would be the case, for example, if the probe were fully inserted
35   into the tissue **36**.   Physical contact with media **35** or tissue **36**
     provides electrical contact with media **35** or tissue **36**.

     Fig. 2 shows a closeup view of the probe tip **37**.   The inner
     electrode **38** and dielectric material **42** are shown.   The inner
40   electrode has an endface **60**.   The endface is preferably about
     10-30 microns across **62**.   The endface may have an exposed
     surface area of about 600 microns^2, for example.   The inner
     electrode **38** can be a cylindrical wire, for example, in which

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5   case endface **60** is circular. In use, the inner electrode is
     eroded by ablation. A larger endface provides a longer probe
     lifetime because more inner electrode material must be eroded
     before probe is no longer useful. A larger endface also
     generally requires more powerful electrical pulses. A smaller
10   endface has a shorter lifetime because it is eroded faster.
     However, a smaller endface can be used with less powerful
     electrical pulses.

     Preferably, switches **24**, **28** can switch in less than 50
15   nanoseconds (switching times less than 10 ns are preferred)
     Preferably, switches **24**, **28** are solid state switches. Solid
     state switches appropriate for use in the present invention are
     available from Eurotek, Inc, located in Morganville, NJ.

20   Preferably, shunt resistor **30** R2 has a resistance much lower
     (e.g. an order of magnitude lower) than the resistance between
     inner **38** and outer **40** electrodes during an electrical discharge.
     In a specific embodiment where endface **60** is 25 microns across,
     on-state resistance (during plasma generation) between
25   electrodes **38**, **40** is about 3kOhm and the shunt resistor R2 is
     about 300 Ohm.

     Discharge resistor **26** and shunt resistor **30** have a resistance
     selected to protect the discharge switch **24** and shunt switch **28**
30   from excessive current. The lowest resistance values of the
     resistors **26**, **30** is set by the maximum current limit of the
     switches. This is a particular concern in embodiments where
     switches **24**, **28** are solid state switches.

35   In operation, switches **24**, **28** are operated alternately. **Fig. 1**
     shows the discharge switch **24** in a closed or conductive state,
     and the shunt switch **28** in an open or nonconductive state.
     Switches **24**, **28** are only in the state shown while a pulse is
     being applied to the tissue. During time periods between
40   pulses, the shunt switch **28** is closed, and discharge switch **24**
     is open.

5   The present apparatus cuts tissue by applying short duration
     (i.e. less than 300 nanoseconds), high voltage pulses (i.e.
     greater than 1.5 kV) to the inner electrode. The pulses are
     created by simultaneously closing discharge switch **24** and
     opening shunt switch **28**. Opening and closing of the switches
10   **24, 28** is controlled by the switch controller **34**. During the
     pulse, the discharge switch is closed, and the shunt switch is
     open. The pulse is actively terminated by opening discharge
     switch and closing shunt switch. The low resistance of the
     shunt resistor **30** compared to the on-state (i.e. with plasma
15   present) resistance provides that the pulse is quickly
     terminated. Active termination of the pulse is greatly
     preferred in the present invention. Active termination of the
     pulse assures that the pulse is stopped abruptly before
     exceeding 300 ns.

20

     Fig. 3 shows a Voltage vs. Time plot of the voltage as measured
     at the probe electrodes **38, 40** during a single rectangular pulse
     53. The pulse **53** has a V-risetime **46** and a V-falltime **48**. In
     the present specification, the V-risetime and V-falltime apply
25   only to Voltage vs. Time plots. The V-risetime **46** is defined as
     the time required for the voltage to change from essentially 0
     Volts (e.g. 100 volts) to 1.5 kV; the V-falltime **48** is defined
     as the time required for the voltage to change from 1.5kV to
     essentially 0 Volts (e.g. 100 volts). A pulse V-duration **54** is
30   defined as the duration the pulse exceeds 1.5kV at the probe
     electrodes **38, 40**.

     Preferably, the voltage pulse has a somewhat rectangular shape
     as shown, with the voltage maintaining a plateau voltage for
35   most of the pulse duration. This feature is provided because
     the capacitor **22** is large enough so that an RC time constant
     (C=capacitor **22** capacitance, R=resistance of circuit during
     discharge) is longer than the pulse duration **54**. In the pulse
     shown, the plateau voltage is about 5kV, the V-risetime and V-
40   falltime are about 5 nanoseconds, and the pulse V-duration **54** is
     about 80 nanoseconds. The short falltime is due to the fast
     closing time of the shunt switch **28** and low resistance of shunt
     resistor R2. Falltime of the pulse is determined by discharge

5   of the internal capacitance of the probe (about 10 pF) through
R2, and by discharge of the internal capacitance of discharge
switch **24** (about 20 pF) through R1+R2. R1+R2 resistance of
about 600 Ohms provides a V-falltime of about 15ns.

10   However, the voltage can change during the pulse duration so
that a plateau voltage is not well defined. The voltage pulse
can even have an 'peaked' shape or any other shape, provided
that the pulse exceeds 1.5kV. Peaked pulse **55**, for example, has
approximately the same V-duration and V-risetime and V-falltime
15   as rectangular pulse **53**, and is well within the scope of the
present invention.

The plateau voltage is somewhat less than the voltage provided
by the high voltage supply **20**. The actual plateau (or peak)
20   voltage measured at the inner electrode depends greatly upon the
impedance of the tissue during plasma formation, and the
impedance of the circuit and probe. Therefore, in order to
generate a desired voltage at the endface, the voltage of the
high voltage source must be considerably higher than the desired
25   endface voltage (e.g. sometimes 50-100% higher).

The voltage pulse preferably has a plateau or peak voltage
between 2kV and 15kV. The V-risetime is less than 100
nanoseconds, preferably less than 50 nanoseconds. The V-
30   falltime is less than 200 nanoseconds, preferably less than 100
nanoseconds, most preferably less than 50 nanoseconds. The
pulse V-duration **54** is less than 300 nanoseconds. More
preferably, the pulse duration is less than 150 nanoseconds, and
most preferably, the pulse duration is less than 100
35   nanoseconds. Pulse duration can even be limited to less than 50
or 25 nanoseconds to yield exceptionally advantageous results
(i.e. efficient cutting of tissue and reduced side effects from
cavitation bubbles). It is noted that, for shorter pulse
duration, the voltage must be higher to provide the same tissue
40   cutting efficacy.

In a preferred embodiment, a series of pulses are applied to
tissue being cut. Pulses are applied at a frequency of about 1-

5   10000 Hz. Since the pulses are so short, this corresponds to a
     duty cycle much less than 0.1%. More preferably, the pulses are
     applied at a rate in the range of about 10-50 Hertz. It is
     important to note that, in the present invention, essentially
     zero charge (i.e. less than 1% of the charge delivered in a
10   single pulse) passes through the probe electrodes **38**, **40** between
     pulses. This prevents the formation of bubbles (e.g. oxygen or
     hydrogen bubbles) at the endface **60**. This is desirable because
     the presence of a bubble on the endface results in plasma
     formation inside the bubble, instead of in the tissue **36** or
15   liquid medium **35**. Plasma formation inside the gas bubble
     strongly reduces pressures and expansion velocity of the
     overheated liquid or tissue, thereby resulting in reduced tissue
     cutting efficacy.

20   **Fig. 4** shows a view of the probe tip during an electrical pulse.
     The probe tip is surrounded by tissue **36** or liquid media **35**.
     Plasma streamers **64** extend from the endface **60**. The plasma
     streamers **64** extend from the endface a distance **66** which may be
     about 20-100 microns (a good depth range for many intraocular
25   surgical procedures). The plasma streamers **64** and ionize,
     evaporate and destroy tissue in a very small region surrounding
     endface **60**. In the present invention, cutting is provided
     mostly by the extremely hot plasma streamers **64**. The plasma
     streamers **64** provide cutting action without causing excessive
30   collateral damage to surrounding tissues.

     The plasma streamers **64** are accompanied by rapidly expanding
     vapor and a shock wave **68** which travels in all directions away
     from the endface **60**. The shock wave helps provide cutting
35   action. For efficient generation of the shock wave, pulse
     duration should be limited to the time required for the shock
     wave to leave the vicinity of where energy is deposited (i.e.
     the vicinity of the plasma streamers). For example, for 50
     micron long plasma streamers, the pulse duration should be
40   limited to about 50 ns, assuming that the shock wave velocity is
     close to the speed of sound in water, 1000m/s).

5   Sharp, high intensity shock waves are a particular advantage
     when cutting hard tissues such as lenses, lens capsules, and
     irises. Therefore, when cutting hard tissues, it is best to use
     relatively short (i.e. less than 75 nanosecond) pulses so that
     strong shock waves are generated.
10
     Fig. 5A shows a method of the present invention in which the
     probe tip **37** is held away from the tissue **36** by a small distance
     80 when the electrical pulse is applied to the probe. Liquid
     medium **35** (e.g. physiological fluid) is located between the
15   tissue **36** and endface **60**. The tissue **36** can be cut even though
     the endface **60** is not in direct contact with the tissue. This
     is because the distance **80** is small enough such that plasma
     streamers **64** and the shock wave **68** propagate into the tissue **36**.
     Generally, plasma streamers can efficiently cut the tissue **36** if
20   the distance **80** is less than about 200 microns.

     Fig. 5B shows a method where the endface **60** is in direct contact
     with tissue. The outer electrode **40** (not shown) is in contact
     with the liquid media **35**, but not in contact with the tissue **36**.
25   The method of **Fig. 5B** generally provides deeper cutting than the
     method of **Fig. 5A** for the same pulse parameters.

     The length and distribution of the plasma streamers **64** depends
     upon the voltage applied, pulse duration, and the surface area
30   of the endface. The larger the surface area of the electrode,
     the lower will be the resistance via normal conduction (without
     plasma) through the liquid **35** and tissue **36**. Therefore, for
     large endface surface area, less energy will be deposited into
     plasma streamer generation. However, very small endface surface
35   area results in rapid etching of the endface and reduced probe
     lifetime. Therefore, an optimal endface size depends upon
     application (energy per pulse and required lifetime the probe).
     Generally, circular endfaces having a diameter from a few
     microns to several tens of microns are preferred.
40
     The length of the plasma streamers can reach about 100 microns,
     and further increases in plasma voltage or pulse duration
     results in branching of the plasma streamers (as shown in **Fig.**

5   4). The depth of the cut in tissue may exceed the length of the
plasma streamers, depending on tissue properties. Generally,
the softer the tissue, the deeper the cut beyond the plasma
streamer length.

10   The rate of plasma streamer development depends on applied
voltage. The plasma streamers develop faster with higher
voltage. The rate of plasma streamer development is measured by
the time required for the resistance between inner and outer
electrodes to change from a high value (e.g. 12-15 kOhm) for
15   ionic conduction to a low value (e.g. 2-5 kOhm) for plasma
conduction. For example, with 23 pF discharge capacitor 22, and
at 1.7 kV, a high to low resistance 90%-10% transition time is
about 110 ns, and at 5kV the high to low resistance 90%-10%
transition time is 12 ns. Therefore, with higher applied
20   voltages, the same size plasma streamer is generated with
shorter pulses. This increases the mechanical confinement of
the shock wave, thus increasing cutting efficiency.

The short V-duration (i.e. less than 200 nanoseconds) of the
25   pulses of the present invention provides a very important
benefit. The short pulse duration provides exceptionally
efficient cutting of tissue for a given amount of energy
applied. This is because of fast ionization due to high
electric fields near the endface, as well as efficient shock
30   wave formation. Energy-efficient cutting provides relatively
high cutting power for a given cavitation bubble size (which is
determined by pulse energy). Therefore the short pulses of the
present invention provide effective cutting with less collateral
damage to surrounding tissues. Active termination of the
35   electrical pulses assures that the electrical pulses do not
exceed a maximum desired duration.

It is also noted that cavitation bubbles can only cut very soft
tissues. The method of the present invention uses plasma to
40   provide cutting. Plasma can cut much harder and more dense
tissues than cavitation bubbles, while producing less collateral
damage. Plasma cutting is enhanced, and cavitation bubble
effects are attenuated by using short (i.e. less than 200

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5   nanosecond), high peak power pulses (i.e. greater than 1000
       Watts).

       In order to generate short, high voltage pulses, it is best to
       use two switches **24, 28** as shown in **Fig. 1.** Closing the shunt
10   switch **28** guarantees that voltage is not applied for a duration
       longer than desired. The shunt switch **28** assures that the pulse
       duration is not defined by an excessively long exponential decay
       constant (e.g. hundreds of nanoseconds). The voltage at the
       endface, however, will be influenced by capacitance and
15   inductance between the shunt switch and probe tip.

       In some cases, impedance matching between circuit **21**, probe **32**
       and plasma streamers **64** is a concern. For the particular device
       described in **Fig. 1**, the impedance of the tissue **36** between
20   inner electrode **38** and outer electrode **40** is about 2-5 kOhms
       during plasma streamer discharge. Therefore, for impedance
       matching, a transmission line having a characteristic impedance
       of 2-5 kOhms can be connected between the probe **32** and circuit
       21.

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       1.5kV is generally the preferred minimum voltage for the method
       of the present invention because 1.5kV is typically the minimum
       voltage required for ionization and plasma streamer formation in
       tissue using sub-microsecond pulses. 15kV is the preferred
30   maximum voltage because it is difficult to rapidly switch
       voltages greater than 15 kV; also, components capable of
       switching voltages greater than 15kV are relatively costly.
       Voltages greater than 15kV can be used in the present method if
       a fast and inexpensive switching device, flexible HV cables and
35   proper microelectrode materials are provided. It is noted that,
       for high voltages, the pulse duration should be shortened.
       Therefore, if very high voltages are used (i.e. greater than 15
       kV), then the switches must be able to produce shorter duration
       pulses.

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       In order to maintain constant per-pulse energy with rectangular
       (plateau) pulses, the pulse duration should scale as $1/V^2$, where
       V is pulse voltage. This assumes that the resistance of the

5   discharge is the same at different voltages. However, the
     resistance tends to decrease with increasing voltage (as well as
     pulse duration), thereby requiring that the pulse duration be
     further shortened to preserver constant per-pulse energy.

10   The electrical pulses of the present invention can also be
     characterized in terms of power dissipated in the tissue. In
     some cases, describing the pulses in terms of power is a more
     useful characterization.

15   **Fig. 6A** shows a semilogarithmic plot of Power vs. Time for a
     pulse according to a preferred embodiment of the present
     invention. The pulse has a P-risetime **74**, a P-falltime **76**, and
     a nonzero P-duration **78** above 500 watts. In the present
     specification, the P-risetime, P-falltime, and P-duration apply
20   only to Power vs. Time plots. The P-risetime is the time
     required for the pulse to change from 50 Watts to 500 Watts.
     The P-falltime is the time required for the pulse to change from
     500 Watts to 50 Watts. In the present invention, the P-risetime
     is less than 100 nanoseconds, preferably less than 75 or 50
25   nanoseconds. In the present invention, the P-falltime is less
     than 150 nanoseconds, preferably less than 75 or 50 nanoseconds.
     After the pulse, the power dissipation preferably falls to 1
     Watt or less, most preferably to essentially zero Watts.
     Preferably, the power dissipation falls from 50 Watts to less
30   than 1 Watt within 100 nanoseconds. This prevents the formation
     of gas bubbles on the endface **60** between electrical pulses. In
     the present invention, the P-duration **78** is less than 300
     nanoseconds. More preferably, the P-duration **78** is less than
     200, 150, or even 75 nanoseconds. Short durations are
35   preferred. Short duration pulses provide more effective cutting
     and less collateral damage to surrounding tissues. The
     risetimes and falltimes can also be defined in terms of changes
     between 800 Watts and 50 Watts.

40   In the present invention, 500 Watts is the minimum power
     dissipation because 500 Watts is approximately a lower limit for
     plasma streamer formation which provides reasonably effective
     cutting. Higher powers (e.g. 800, 1000 or 1500 Watts) provide

5   more powerful plasma streamers which develop more quickly and
      provide more effective cutting.   Therefore, if higher power
      pulses are used, then pulses can have a shorter duration and
      still provide equally effective cutting.   The duration **78** can
      also be defined in terms of these high power levels.

10

      However, the threshold for plasma streamer formation depends
      somewhat on the endface **60** surface area. More specifically, 500
      Watts is the plasma streamer formation threshold for a circular
      endface of 25 microns diameter.   The threshold for plasma
15   streamer formation will be somewhat higher for larger surface
      area endfaces **60**.   The threshold for plasma streamer formation
      will be somewhat lower for smaller surface area endfaces **60**.
      This is because a large endface tends to conduct current with
      normal, ionic conduction, thereby reducing the power available
20   for plasma streamer formation.

      Fig. 6B illustrates another characterization of the present
      method.   A linear plot of pulse power versus time is shown.   The
      pulse has a peak power dissipation **110** (in this specific
25   example, the peak is slightly in excess of 2000 Watts).   The
      peak **110** defines a 90%-of-peak level **112** and a 10%-of-peak level
      114.   In the present invention, the pulse has a 10%-to-90%
      risetime **116** of less than 100 nanoseconds.   Preferably, the
      risetime is much less than 100 nanoseconds (e.g. less than 50
30   nanoseconds).   Also in the present invention, the pulse has a
      90%-to-10% falltime **118** of less than 200 nanoseconds.   Also in
      the present invention the power dissipation is greater than 500
      Watts for a duration less than 300 nanoseconds.   Preferably, the
      duration above 500 Watts is less than 200 or 150 nanoseconds.
35   The pulse can also have a peak greater than 800 Watts, 1000
      Watts, or 1500 Watts.   The peak power dissipation **110** depends
      upon the application.   For cutting relatively soft tissues, peak
      110 should be relatively low; for cutting hard tissues, peak **110**
      should be relatively high.   For example, for cutting lenses or
40   lens capsules, peak power may be greater than 2000 Watts.

      Fig. 7 shows an alternative embodiment of a circuit **90** according
      to the present invention.   The circuit **90** does not have the

5   shunt switch **28**, but only a shunt resistor **92**. In this case,
the shunt resistor **92** should have a resistance lower than the
normal resistance (due to ionic conduction) between inner and
outer electrodes (about 12-15 kOhms when a 25 micron diameter
endface is used), and comparable with the resistance of the
10   plasma streamer discharge (about 3kOhm). For example, the shunt
resistor **92** can be about 2-4 kOhms. A shunt resistor strongly
reduces the power dissipation and shortens the risetime and
falltime of the discharge, but does not strongly effect the
plasma streamer development. This is because the shunt resistor
15   carries relatively little current while plasma streamers exist.
The pulse falltime is determined in this case by capacitor **22**
and R1+R2 time constant. For pulse V- or P-duration less than
200 ns, capacitor **22** should have a capacitance less than about
70 pF. The circuit **90** produces pulses with relatively long
20   falltimes compared to circuit **21**. However, circuit **90** may be
preferably for many applications because of lower cost as a
result of requiring only one switch.

Fig. 8 shows a plot of power vs. time for a pulse train
25   according to the present invention. The pulse train shown has a
frequency of about 100 Hz, but can have a frequency anywhere in
the range of about 1-10000 Hz. A pulse train provides
essentially continuous cutting. The pulses are so short that
they appear as spikes in the plot of **Fig. 8**. Preferably, the
30   power dissipation in durations **100** between pulses is so low that
the pulse train has an average power dissipation less than 0.2
Watts, more preferably less than 0.05 Watts or less than 0.01
Watts.

35   The present invention is particularly well suited for use in
microsurgical procedures such as intraocular surgery. The
present invention can be used in retinal surgery, cataract
surgery, capsulotomy, irridotomy, as well as other intraocular
surgical procedures.
40
The following examples are useful pulser settings for different
surgical procedures. The settings are not necessarily

5   optimized, and may be improved. In all the following examples,
    the endface is circular and 25 microns in diameter.

    <u>Slow dissection of epiretinal membranes:</u>
         Pulse energy: 86 uJ,
10   Pulse peak power: 520W,
         Duration above 500W: 46 ns
         50-500 Watt P-risetime: 18 ns
         500-50 Watt P-falltime: 148 ns
         Peak voltage 2.2 kV.
15   Repetition rate: 10-20 Hz

    <u>Fast dissection of epiretinal membranes:</u>
         Pulse energy 158 uJ,
         Pulse peak power 1150W,
20   Duration above 500W: 138 ns
         50-500 Watt P-risetime: 7 ns
         500-50 Watt P-falltime: 118 ns
         Peak voltage 2.6 kV.
         Repetition rate: 30-50 Hz

25

    <u>Dissection of lens capsule:</u>
         Pulse energy 250 uJ,
         Pulse peak power 2100W,
         Duration above 500W: 160 ns
30   50-500 Watt P-risetime: 6 ns
         500-50 Watt P-falltime: 110 ns
         Peak voltage 3.1 kV.
         Repetition rate: 20-40 Hz

35 <u>Dissection of lens capsule:</u>
         Pulse energy 187 uJ,
         Pulse peak power 2200W,
         Duration above 500W: 124 ns
         50-500 Watt P-risetime: 4 ns
40   500-50 Watt P-falltime: 80 ns
         Peak voltage 3.3 kV.
         Repetition rate: 20-40 Hz

5   It will be clear to one skilled in the art that the above
    embodiment may be altered in many ways without departing from
    the scope of the invention.   Accordingly, the scope of the
    invention should be determined by the following claims and their
    legal equivalents.

CLAIMS

What is claimed is:

1. A method for electrosurgically cutting tissue surrounded by liquid using an electrosurgical probe, wherein the electrosurgical probe has a first electrode and a second electrode, and wherein the first electrode has an endface with area A in close proximity to the tissue, the method comprising the step of:

   a) applying to the first electrode an electrical pulse such that plasma streamers are formed from the electrode endface by an electrical discharge, wherein the electrical discharge starts in the tissue or the liquid, wherein the endface area A is less than 10000 microns^2, and wherein the electrical pulse has a pulse power dissipation which:

      i) is greater than 500 Watts for a nonzero duration less than 300 nanoseconds,

      ii) rises from 50 Watts to 500 Watts in less than 100 nanoseconds;

      iii) falls from 500 Watts to 50 Watts in less than 150 nanoseconds.

2. The method of claim 1 wherein pulse power is greater than 500 Watts for a duration less than 200 nanoseconds.

3. The method of claim 1 wherein pulse power is greater than 500 Watts for a duration less than 150 nanoseconds.

4. The method of claim 1 wherein pulse power is greater than 800 Watts for a duration less than 200 nanoseconds.

5. The method of claim 4 wherein pulse power falls from 800 Watts to 50 Watts in less than 150 nanoseconds.

6. The method of claim 1 wherein pulse power is greater than 1500 Watts for a duration less than 200 nanoseconds.

7. The method of claim 1 wherein pulse power rises from 50 W to 500 W in less than 50 nanoseconds.

8. The method of claim 1 wherein pulse power falls from 500 W to 50 W in less than 100 nanoseconds.

9. The method of claim 1 wherein the tissue is selected from the group consisting of lenses, lens capsules, retinal tissue, and irises.

10. The method of claim 1 wherein step (a) is repeated at a rate in the range of 10-50 Hertz.

11. The method of claim 1 wherein step (a) is repeated at a rate in the range of 1-10000 Hertz.

12. The method of claim 11 wherein between electrical pulses electrical power dissipated in the tissue is sufficiently low so that no gas bubbles are formed on the electrodes between electrical pulses.

13. The method of claim 11 wherein an average power dissipation is less than 0.2 Watts.

14. The method of claim 11 wherein an average power dissipation is less than 0.05 Watts.

15. The method of claim 1 wherein the endface area A is in the range of 200-1000 microns^2.

16. A method for electrosurgically cutting tissue surrounded by liquid using an electrosurgical probe, wherein the electrosurgical probe has a first electrode and a second electrode, and wherein the first electrode has an endface with area A in close proximity to the tissue, the method comprising the step of:

a) applying to the first electrode an electrical pulse such that plasma streamers are formed from the electrode endface by an electrical discharge, wherein the electrical discharge starts in the tissue or the liquid, wherein the endface area A is less than 10000 microns^2, and wherein the electrical pulse has a pulse power dissipation with a peak power dissipation, wherein the pulse power dissipation:

  i) is greater than 500 Watts for a nonzero duration less than 300 nanoseconds,

  ii) rises from 10% of the peak power dissipation to 90% of the peak power dissipation in less than 100 nanoseconds;

  iii) falls from 90% of the peak power dissipation to 10% of the peak power dissipation in less than 200 nanoseconds.

17. The method of claim 16 wherein the peak power dissipation is greater than 800 Watts.

18. The method of claim 16 wherein the peak power dissipation is greater than 1100 Watts.

19. The method of claim 16 wherein the peak power dissipation is greater than 1500 Watts.

20. The method of claim 16 wherein pulse power is greater than 500 Watts for a duration less than 200 nanoseconds.

21. The method of claim 16 wherein pulse power is greater than 500 Watts for a duration less than 150 nanoseconds.

22. The method of claim 16 wherein pulse power falls from 90% of the peak power dissipation to 10% of the peak power dissipation in less than 150 nanoseconds.

23. The method of claim 16 wherein the tissue is selected from the group consisting of lenses, lens capsules, retinal tissue, and irises.

24. The method of claim 16 wherein step (a) is repeated at a rate in the range of 10-50 Hertz.

25. The method of claim 16 wherein step (a) is repeated at a rate in the range of 1-10000 Hertz.

26. The method of claim 25 wherein between electrical pulses electrical power dissipated in the tissue is sufficiently low so that no gas bubbles are formed on the electrodes between electrical pulses.

27. The method of claim 25 wherein an average power dissipation is less than 0.2 Watts.

28. The method of claim 22 wherein an average power dissipation is less than 0.05 Watts.

29. The method of claim 17 wherein the endface area A is in the range of 200-1000 microns^2.

30. A method for electrosurgically cutting tissue surrounded by liquid using an electrosurgical probe, wherein the electrosurgical probe has a first electrode and a second electrode, and wherein the first electrode has a endface with area A in close proximity to the tissue, the method comprising the step of:

a) applying to the first electrode an electrical pulse such that plasma streamers are formed from the endface by an electrical discharge, wherein the electrical discharge starts in the tissue or the liquid, wherein the endface area A is less than 10000 microns^2, and wherein the electrical pulse has a pulse voltage which:

i) is at least 1.5 kilovolts for a nonzero duration less than 300 nanoseconds;

ii) rises from 100 Volts to 1.5kV in less than 100 nanoseconds;

iii) falls from 1.5kV to 100 Volts in less than 300 nanoseconds.

31. The method of claim 30 wherein pulse voltage is greater than 1.5 kV for a duration less than 200 nanoseconds.

32. The method of claim 30 wherein pulse voltage is greater than 1.5 kV for a duration less than 150 nanoseconds.

33. The method of claim 30 wherein pulse voltage is greater than 2kV for a duration less than 300 nanoseconds.

34. The method of claim 30 wherein pulse voltage is greater than 2.5kV for a duration less than 200 nanoseconds.

35. The method of claim 30 wherein the endface area A is in the range of 200-1000 microns^2.

36. The method of claim 30 wherein pulse voltage rises from 100 Volts to 1.5kV in less than 50 nanoseconds.

37. The method of claim 30 wherein pulse voltage falls from 1.5kV to 100 Volts in less than 200 nanoseconds.

38. The method of claim 30 wherein pulse voltage falls from 1.5kV to 100 Volts in less than 100 nanoseconds.

39. The method of claim 30 wherein the tissue is selected from the group consisting of lenses, lens capsules, retinal tissue, and irises.

40. The method of claim 30 wherein step (a) is repeated at a rate in the range of 10-50 Hertz.

41. The method of claim 30 wherein step (a) is repeated at a rate in the range of 1-10000 Hertz.

42. The method of claim 41 wherein between electrical pulses voltage between the electrodes is sufficiently low so that no gas bubbles are formed on the electrodes between electrical pulses.

43. The method of claim 41 wherein an average power dissipation is less than 0.2 Watts.

44. The method of claim 41 wherein an average power dissipation is less than 0.05 Watts.

45. An apparatus for electrosurgically cutting tissue, comprising:

   a) a high voltage source for providing a voltage of at least 2 kiloVolts;
   b) a probe having a first electrode for applying a high voltage pulse to the tissue, and a second electrode;
   c) a discharge switch connected between the high voltage source and the first electrode so that, when closed, the discharge switch applies high voltage to the first electrode;
   d) a shunt switch connected between the first electrode and the second electrode.

46. An apparatus for electrosurgically cutting tissue, comprising:

   a) a high voltage source for providing a voltage of at least 2 kiloVolts;
   b) a probe having a first electrode for applying a high voltage pulse to the tissue, and a second electrode;
   c) a discharge switch connected between the high voltage source and the first electrode so that the discharge switch applies high voltage to the first electrode when closed;

5   d) a shunt resistor connected between the first electrode and
              the ground electrode, wherein the shunt resistor has a
              resistance less than a normal state resistance between
              the first electrode and second electrode.

10   47. The apparatus of claim 46 wherein the shunt resistor has
   a resistance in the range of 1-5kOhm.

# 1/6
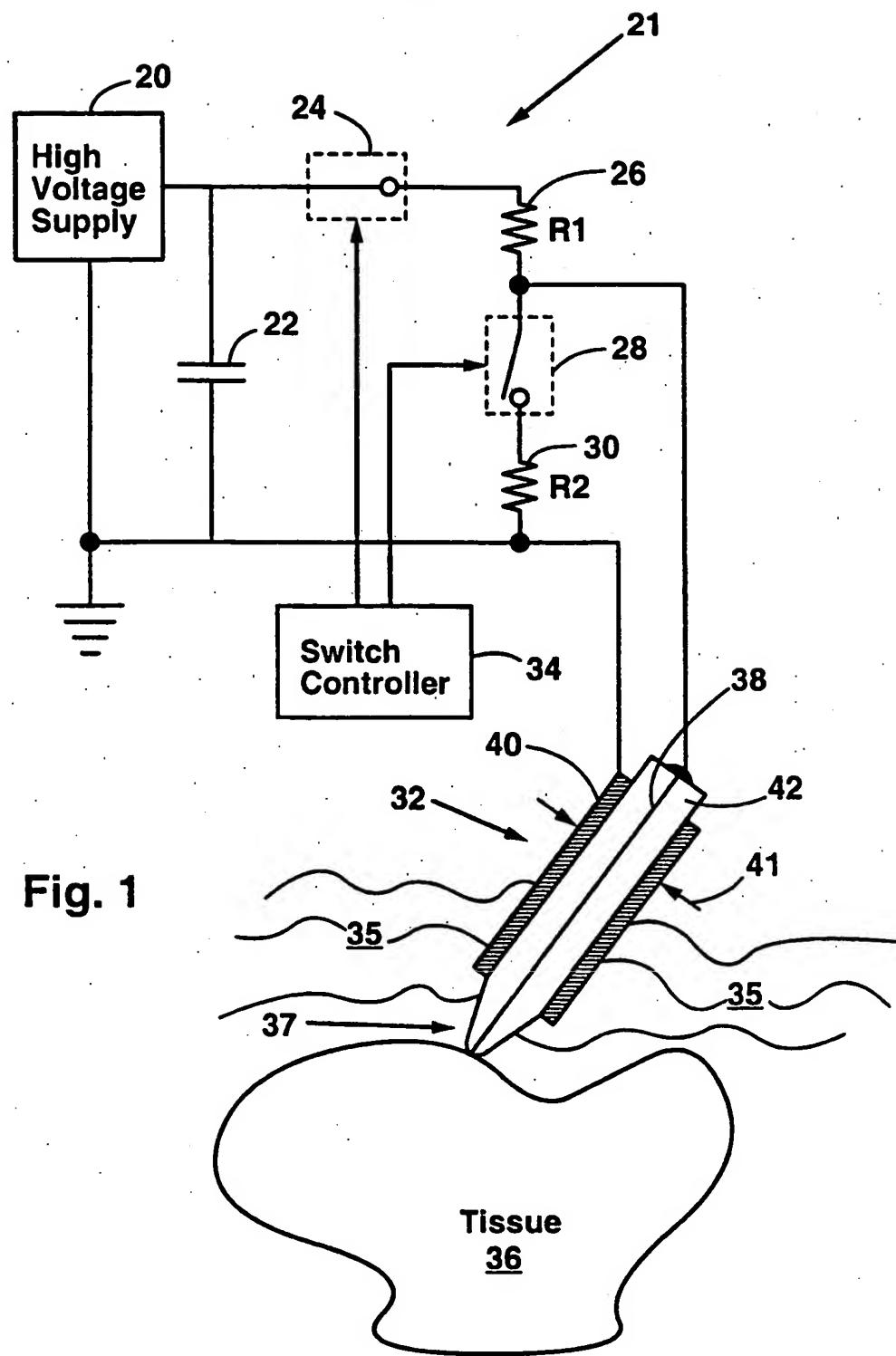
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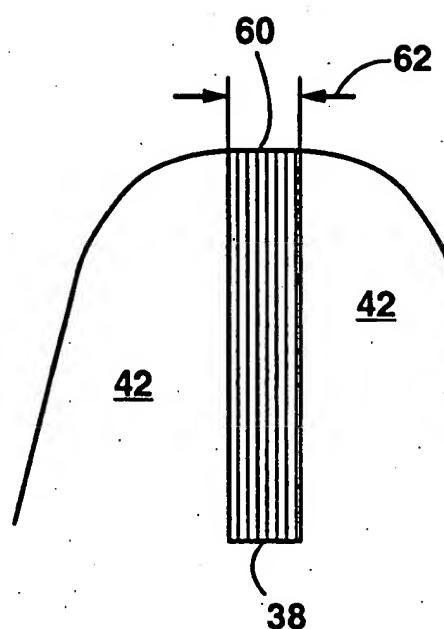
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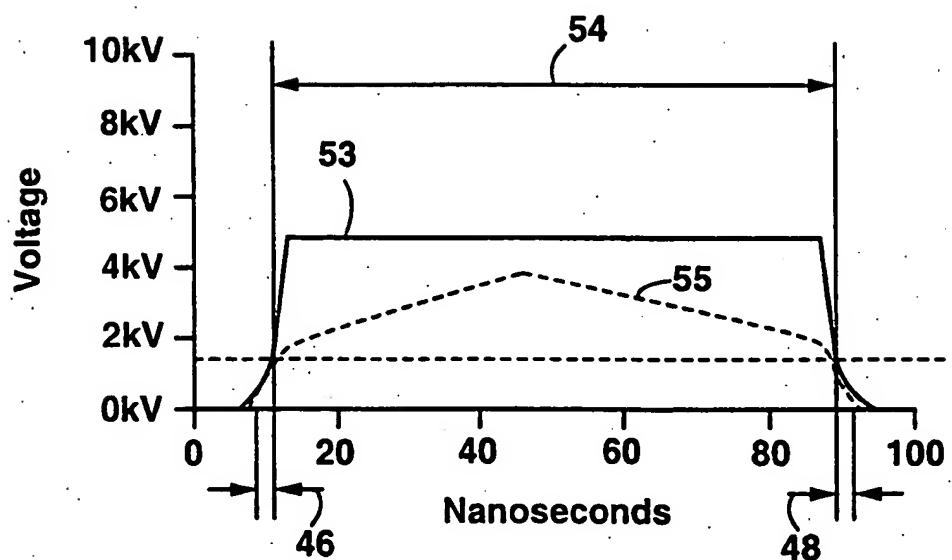
Fig. 3

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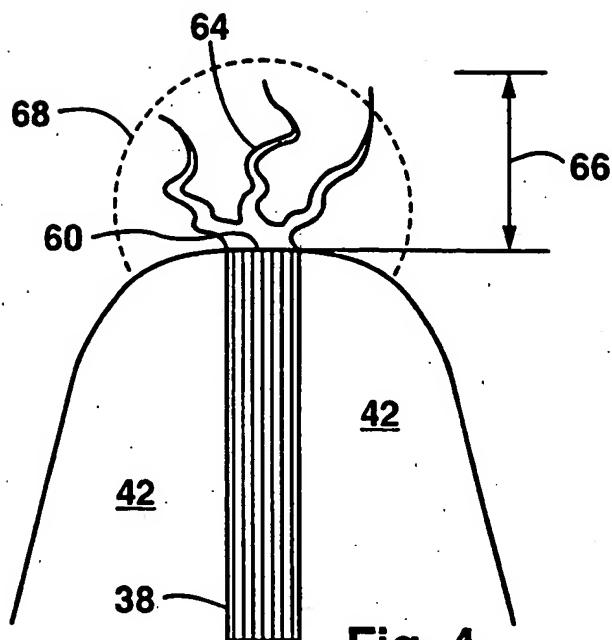
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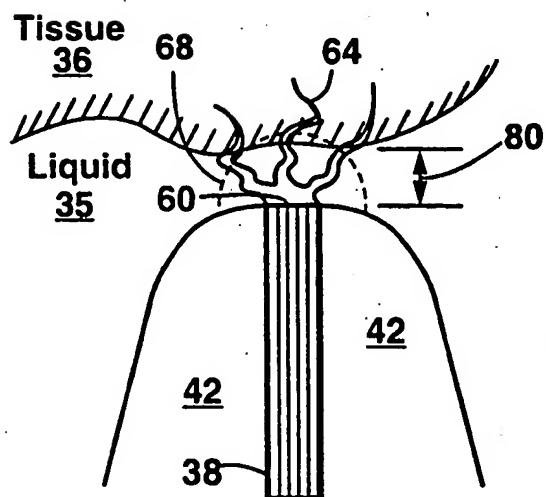
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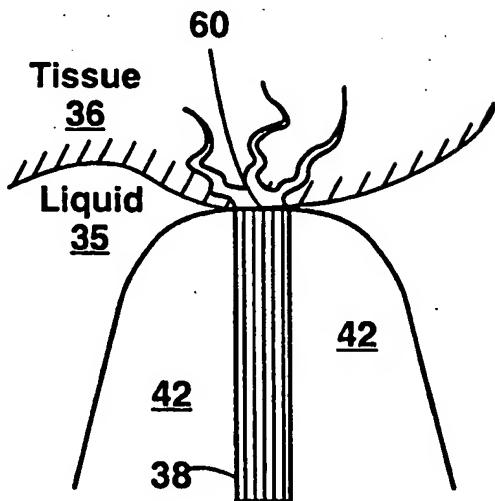
Fig. 5B

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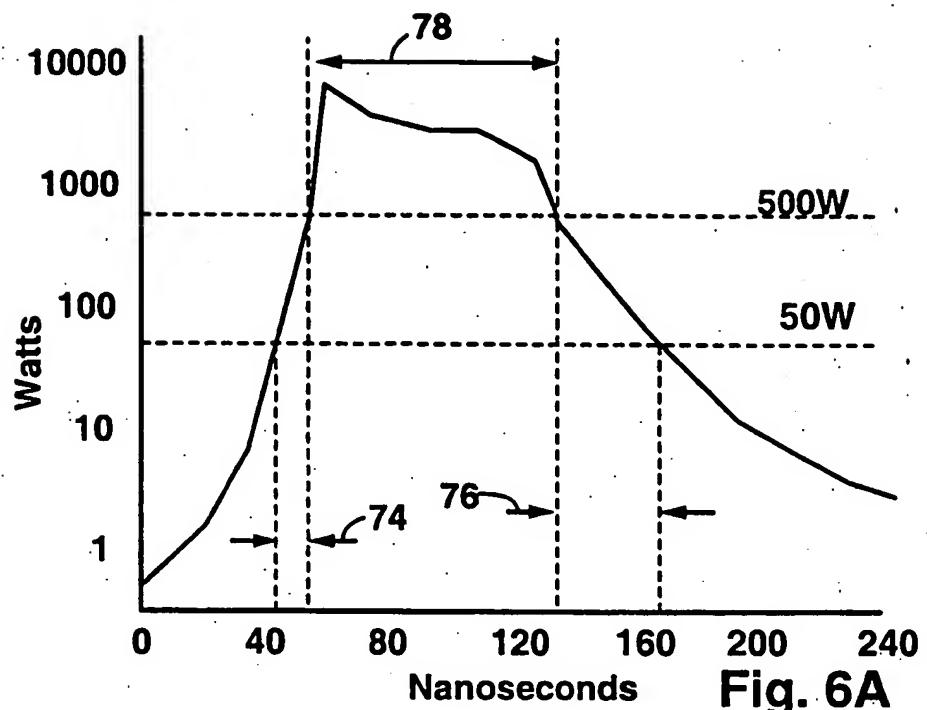
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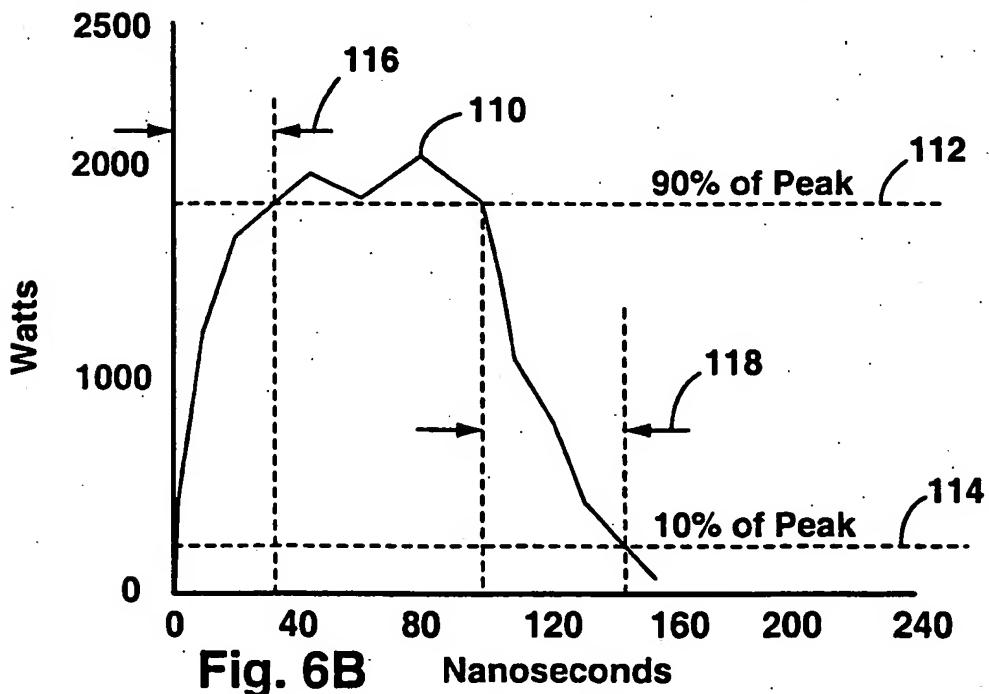
Fig. 6B

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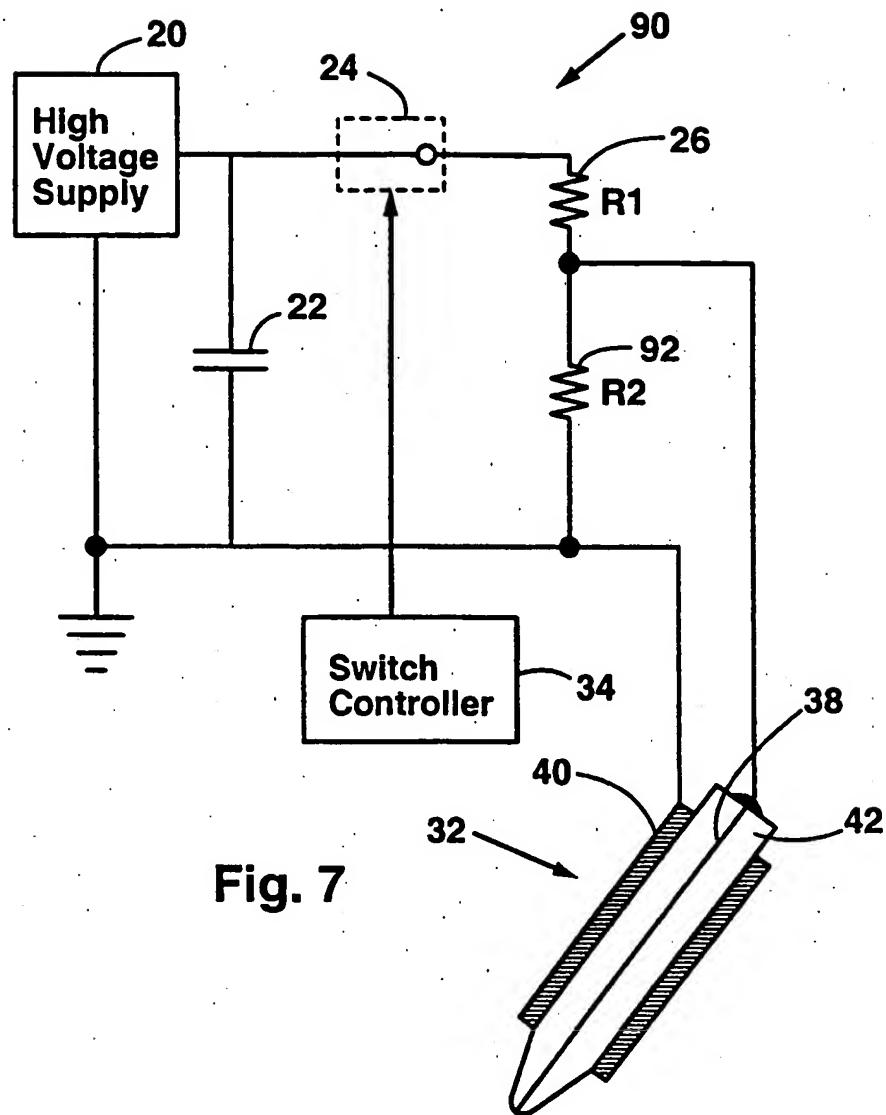
Fig. 7

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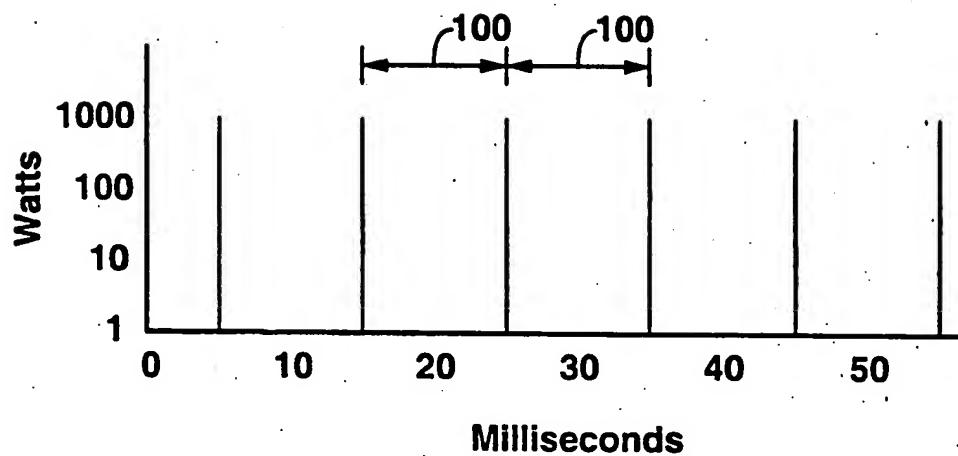
Fig. 8

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :A61B 18/12

US CL :606/39, 45, 48

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 606/34, 37-41, 45-50

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	DANIEL PALANKER et al., Electrical alternative to pulsed fiber-delivered lasers in microsurgery, Journal of Applied Physics Vol. 81, No. 11, 1 June 1997, pages 7673-7680.	30-44

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)		
		"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
09 MAY 2000	06 JUN 2000

Name and mailing address of the ISA/US	Authorized officer
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